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14. ABSTRACT
This main objective of this project is to construct an optical pump system, which would allow us to carry out optical studies of Er:GaN materials under 980 nm resonant excitation. The results obtained from the optically pumped studies will be utilized to guide crystal growth and laser design. During the supporting period, we have accomplished the following tasks:
• Successfully completely the installation of a high power 980 laser. The system is dedicated to the studies of the optical and lasing properties of Er:GaN crystals.

15. SUBJECT TERMS
Er doped GaN, gain medium, high energy laser, optical pump

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					19b. TELEPHONE NUMBER
					806-834-5383

Report Title

Final Report: Erbium Doped GaN Lasers by Optical Pumping

ABSTRACT

This main objective of this project is to construct an optical pump system, which would allow us to carry out optical studies of Er:GaN materials under 980 nm resonant excitation. The results obtained from the optically pumped studies will be utilized to guide crystal growth and laser design. During the supporting period, we have accomplished the following tasks:

• Successfully completely the installation of a high power 980 laser. The system is dedicated to the studies of the optical and lasing properties of Er:GaN crystals.

• Successfully attained for the first time freestanding Er:GaN wafers of 2-inches in diameter with a thickness on the millimeter scale. These freestanding wafers were obtained via growth by hydride vapor phase epitaxy (HVPE) in conjunction with a laser-lift-off (LLO) process. An Er doping level of 1.4 × 10^20 atoms/cm3 has been confirmed by secondary ion mass spectrometry measurement.

• Carried out optical studies of Er:GaN under 980 nm optical pumping.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. “Er doped GaN – Growth, properties and application, PRE’16 6th Int’l workshop on Photoluminescence in Rare-Earth, June 8-10, Greenville, SC, invited.

Number of Presentations: 1.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Jingyu Lin - Elected Fellow of the Optical Society of America (2016)
Hongxing Jiang - Elected Fellow of SPIE (2015)

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

see attached

Technology Transfer

Final Report

ARO Agreement No: W911NF-15-1-0004
Project Title: Erbium Doped GaN Lasers by Optical Pumping
PI Name: Jingyu Lin & Hongxing Jiang
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I. Summary of Progress

High energy and high power solid-state lasers have enabled a variety of applications which have had and will continue to have profound and far-reaching impacts on emerging technologies. The optical gain medium is the heart of a high energy laser (HEL) system. Comparing with the presently dominant gain material for HEL of Nd doped yttrium aluminum garnet (Nd:YAG), the most outstanding property of GaN as a host material for HEL application is its outstanding thermal properties. The thermal conductivity GaN is very high (κ = 230 W/m·K) and is more than one order of magnitude higher than YAG (κ = 14 W/m·K), while its thermal expansion coefficient ($\alpha \approx 4 \times 10^{-6}$ °C^{-1}) is about 2 times smaller than that of YAG ($\alpha \approx 8 \times 10^{-6}$ °C^{-1}). These together makes Er doped GaN (Er:GaN) an excellent gain material with a potential to outperform Nd:YAG lasers by a factor of about 60 – 120. Another important advantage of GaN for HEL application is its significantly higher fracture toughness figure than YAG due to its excellent mechanical property. Moreover, the 1.54 µm emission resulting from the intra-4f transition from the first excited manifold ($^4I_{13/2}$) to the ground state ($^4I_{15/2}$) in Er^{3+} ions is a relatively eye-safe wavelength, in that the upper limit of eye-safe laser exposure at 1.5 µm is more than 4 orders of magnitude higher than that of the wavelength range below or close to 1 µm.

To realize the full potential of Er:GaN as a gain medium for HEL, however, Er:GaN bulk crystals in large wafer sizes are required to enable the fabrication of gain media in disk, rod or slab geometry to provide high energy and high power operation. Furthermore, a resonant excitation (e.g. 980 nm) is more desirable than a non-resonant excitation as resonant excitation involves direct transition between the ground state to a higher-lying inner 4f manifold in Er^{3+} ions without invoking a non-radiative energy transfer, hence generating a much smaller amount of heat than a non-resonant excitation. Additionally, 980 nm pump appears to be a preferred pump wavelength in terms of providing the best trade-off between the optical absorption length, minimizing the quantum defect and managing the constrains in hydride vapor phase epitaxy (HVPE) growth for obtaining Er:GaN crystals with a reasonable thickness. Furthermore, the absorption cross section of Yb^{3+} at 980 nm is about an order of magnitude larger than that of Er^{3+}. Under 980 nm pump, in an Er and Yb co-doped GaN, from Yb^{3+} the energy can transferred resonantly to the $^4I_{11/2}$ state of Er^{3+}. Therefore, under 980 nm pump, Yb and Er co-doping can enhance the effective excitation cross section by at least one order of magnitude.

During the supporting period, we have accomplished the following tasks:

1. Successfully attained for the first time freestanding Er:GaN wafers of 2-inches in diameter with a thickness on the millimeter scale. These freestanding wafers were obtained via growth by hydride vapor phase epitaxy (HVPE) in conjunction with a laser-lift-off (LLO)

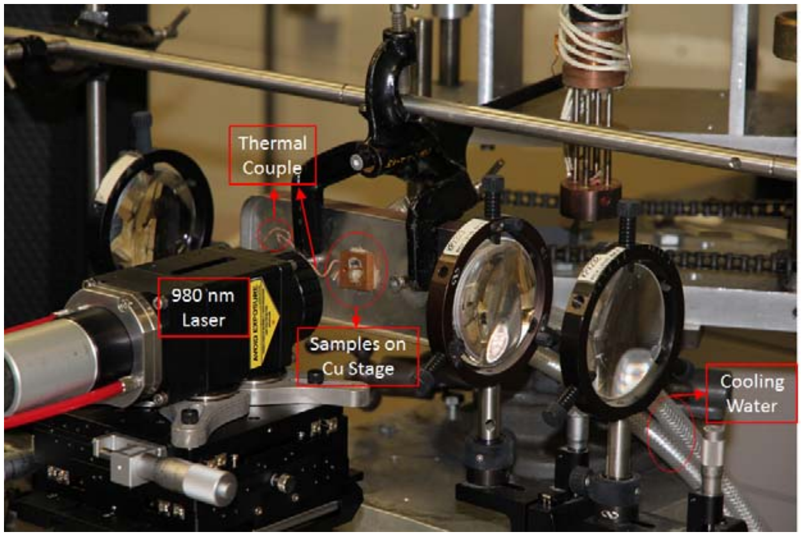

Fig. 1 Experimental setup for optically pumped studies under 980 nm laser excitation.

process. An Er doping level of 1.4×10^{20} atoms/cm^3 has been confirmed by secondary ion mass spectrometry measurement.

2. Successfully completely the installation of a high power 980 laser, as shown in Fig. 1. The system is dedicated to the studies of the optical and lasing properties of Er:GaN crystals.
3. Carried out optical studies of Er:GaN under 980 nm optical pumping.

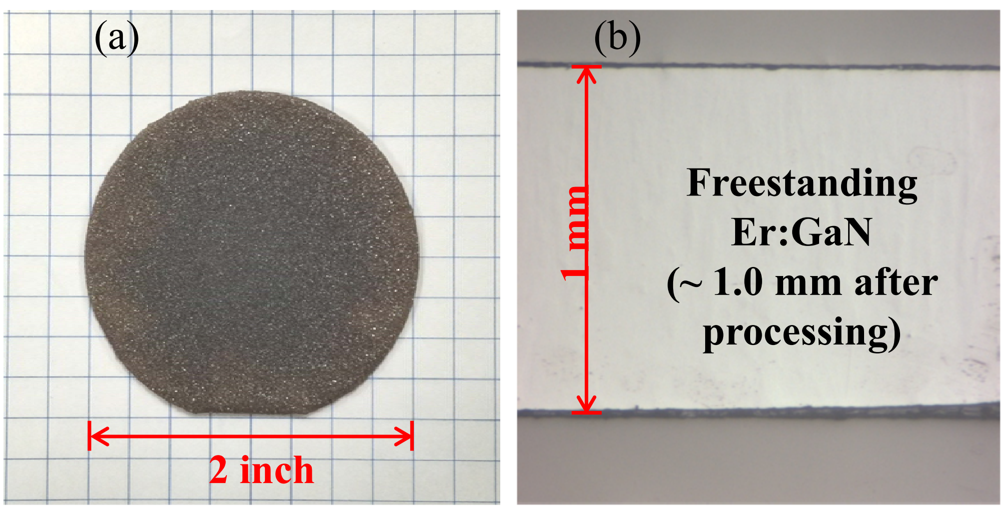

Fig. 2 Optical images of a freestanding Er-doped GaN wafer (1.2 mm in thickness) grown by HVPE: (a) Top view; (b) Cross-sectional view of a piece of freestanding sample obtained via laser-lift-off having a thickness of 1.0 mm after polishing.

Figure 2(a) shows an optical image of a free-standing 2-inch Er:GaN wafer with a thickness 1.2 mm obtained by HVPE (at a growth rate of about 200 µm/hour, for 6 hours) followed by LLO processing. Figure 2(b) shows the cross-sectional view taken by optical microscopy of this sample after polishing, which indicates that this freestanding Er:GaN wafer had a thickness of 1.0 mm after polishing. Figure 3 compares the photoluminescence (PL) emission spectra

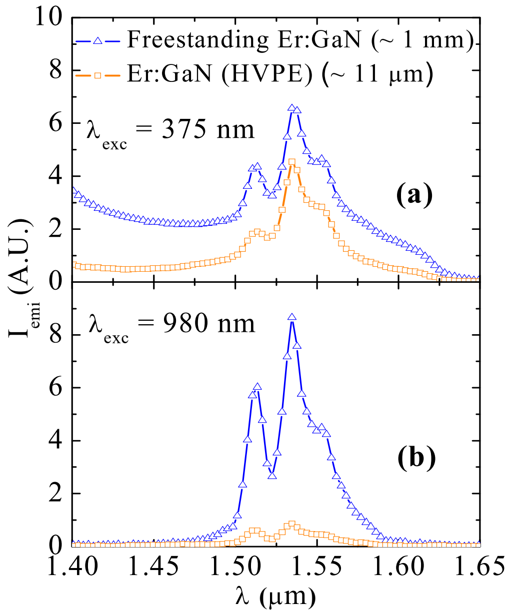

Fig. 3 Comparison of room temperature PL spectra of freestanding Er:GaN samples of two different thicknesses of 1 mm and 11 μm, excited by (a) band-edge excitation at λ_{exc} = 375 nm and (b) resonant excitation at λ_{exc} = 980 nm.

measured at room temperature for freestanding Er:GaN samples of 1 mm and 11 μm in thicknesses for (a) band-edge non-resonant excitation at λ_{exc} = 375 nm and (b) resonant excitation at λ_{exc} = 980 nm. The strong 1.54 μm peak emission line originating from the intra-4f transition of Er dopants was clearly observed in both cases. The measured PL emission spectral shapes under both 375 nm and 980 nm pump wavelengths are quite similar. However, compared to the thin Er:GaN sample which had a thickness of only 11 μm, the freestanding Er:GaN with a thickness of ~ 1 mm exhibits a much stronger PL emission intensity under 980 nm resonant excitation, whereas both thin and thick Er:GaN samples have a comparable PL emission intensity under band-edge non-resonant 375 nm excitation. This can be explained by the fact that the band-edge excitation at 375 nm is predominantly exciting the electron and hole pairs in the GaN host, which has a much small absorption length (< 2 μm). This means that the 375 nm photons are completely absorbed within the top surface of 2 μm. Therefore, increasing the sample thickness to 1 mm does not further increase optical absorption at 375 nm and PL emission intensity at 1.54 μm. In sharp contrast, 980 nm resonant excitation has an excitation cross section of about 2.2×10^{-21} cm^2 and an optical absorption length > 1 mm. Thus, the 1 mm freestanding Er:GaN wafer takes advantage of large thickness, which allows it to absorb much more of the excitation laser's power at 980 nm than the 11 μm thick wafer. This in turn leads to a much higher emission intensity at 1.54 μm for thick Er:GaN wafer.

The freestanding Er:GaN materials were cut into square shape with different sizes and their emission properties around 1.5 μm were studied under 980 nm laser excitation. As shown in Fig. 4(a), the PL emission intensity near spectra of 1.5 μm increases with the sample size under 980 nm pump at an excitation power density of 1 kW/cm^2. As shown in Fig. 4(b), the 1.5 μm emission intensity increases linearly with excitation power density for 4 mm^2 size sample, whereas the 1.5 μm emission intensity increases sub-linearly with excitation power density for a 25 mm^2 mm size sample. The results imply that the cooling mechanism we have implemented is

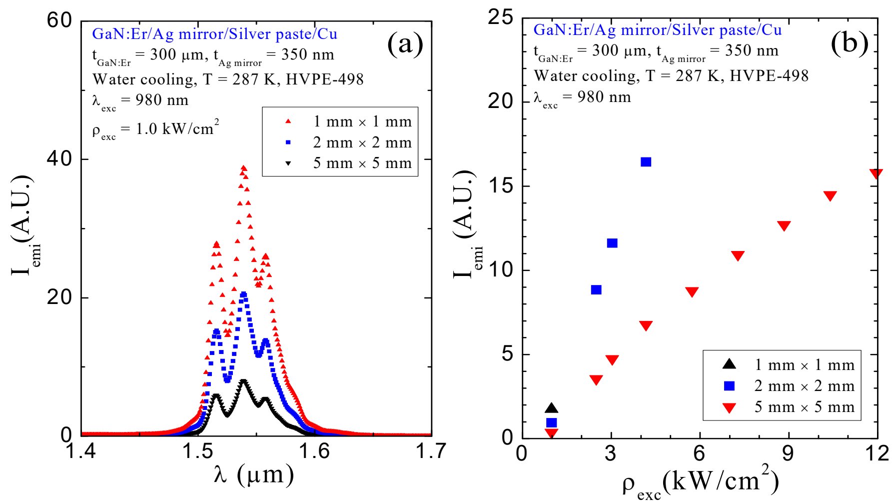

Fig. 4 Comparison of PL emission properties of Er:GaN samples of three different sizes: (a) PL spectra; (b) integrated emission intensity near 1.5 μm vs the excition power density.

not good enough to remove the heat generate during the optical excitation for large samples. We are in the process of improving both the material quality and the cooling mechanisms.

In summary, the DURIP support has enabled our group to construct an optical pump system, which allows us to carry out optical studies of Er:GaN materials under 980 nm resonant excitation. The results obtained from the optically pumped studies will be very useful for guiding crystal growth and laser design.

II. Publications:

1. Z. Y. Sun, J. Li, W. P. Zhao, J. Y. Lin, and H. X. Jiang, "Toward the realization of erbium-doped GaN bulk crystals as a gain medium," submitted to Appl. Phys. Lett.